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# Impact of Radiation Protection Philosophy on Shielding Design Optimization for a Marine SMR

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## 1. Introduction

In 2023 the International Maritime Organization (IMO) adopted a revised GHG strategy that sets the sector on a pathway to net-zero emissions by or around 2050, with indicative checkpoints for 2030 and 2040 [1]. This trajectory compels deep decarbonization options for ocean-going vessels. Among candidate technologies, pressurized water reactor (PWR)–type Small Modular Reactors (SMRs) are technically compelling for commercial propulsion; however, their adoption hinges on solving a key marine engineering bottleneck: a radiation shielding system that is effective yet frugal in mass and volume, both of which are at a premium on ships.

This study quantifies how the underlying radiation protection philosophy propagates into shield mass for a conceptual 300 MWth marine SMR-PWR. Specifically, (i) a design constrained to the ICRP occupational dose limits (with ALARA applied as an optimization process) and (ii) a literature-based relaxed scenario set at 100 mSv·y⁻¹ for sensitivity analysis are contrasted, The second option was motivated by epidemiology indicating that risks at or below ~100 mSv are difficult to detect statistically. This paper determines the minimum shield mass meeting each criterion to provide a quantitative basis for rational shielding decisions in marine applications.

**Table 1. Target Nuclear Ships**

| Class | ULCV |
|---|---|
| **Capacity [TEU]** | 15,000 |
| **DWT [tons]** | 220,000 |
| **L x B x D [m]** | 400 x 60 x 21 |

## 2. Methodology

### *2.1. Radiation Protection Criteria and Dose Evaluation*

Regulatory constraint and ALARA. In this work, dose limits and ALARA are treated distinctly. The design constraint follows ICRP occupational dose limits: 20 mSv per year averaged over 5 years with no more than 50 mSv in any single year. ALARA is then applied as the process of reasonable minimization within those limits. "ICRP-limit case" is referred rather than "ALARA ≤ 20mSv·y⁻¹."[2]

Relaxed scenario for sensitivity (100 mSv·y⁻¹). For comparison, a literature-based relaxed scenario is introduced with the annual worker dose cap of 100 mSv·y⁻¹ to probe mass savings potential. This is not an endorsed regulatory standard; it is a sensitivity setting informed by evidence that the epidemiological detection of increased cancer risk is weak at ≲ 100 mSv. This is also motivated by the fact that policy/regulatory has uncertainty [3, 4].

**Table 2. Summarized Radiation Protection Philosophies**

| Item | ALARA | AHARS |
|---|---|---|
| **Full Name** | As Low As Reasonably Achievable | As High As Relatively Safe |
| **Underlying Model** | LNT (Linear No-Threshold) Model | Threshold / Hormesis Model |
| **Core Philosophy** | Any radiation dose is potentially harmful | A safe dose level (threshold) exists |
| **Engineering Task** | Dose must be minimized (Dose Minimization) | Dose must be kept below a safe limit (Dose Optimization) |

The raw dose rate is converted to a realistic annual worker dose using an exposure scale factor that accounts for a capacity factor ($C_f$, 0.6) and the daily working hours of the crew ($T_w$, 8 hours), as shown in the next Equation:

$$D_{worker} = D_{raw} \times C_f \times \frac{T_w}{24}$$

Dose conversion from particle fields to effective dose uses ICRP Publication 116 coefficients.

This paper evaluates the "watch-stander" point at the outer biological shield plus 5 m along the mid-plane (r = R_outer + 5 m, z = 0). The Monte Carlo/point-kernel model yields the instantaneous effective dose rate E ($r_0$) [mSv·h⁻¹] at this point, combining neutron and gamma contributions.

### *2.2. Shielding Configuration and Materials*

In this study, a Savannah-style dual shielding configuration was adopted, consisting of an inner high-Z liner (lead) and an outer biological shield (concrete). Conventional marine reactors often required a very large secondary shield outside the containment vessel, accounting for a significant fraction of the plant weight.

By introducing a compact high-density lead liner and an optimized concrete layer, the present configuration provides effective attenuation of both neutrons and gamma rays while minimizing the overall shielding mass.

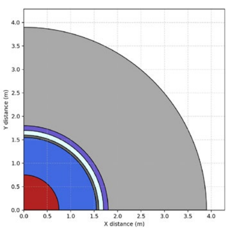
The design philosophy is as follows: the inner lead layer strongly suppresses both primary and capture gamma rays due to its high atomic number, while the outer concrete layer provides bulk attenuation of moderated neutrons as well as residual gamma rays. Concrete is also structurally advantageous, offering both hydrogenous components (for neutron slowing down) and medium-Z elements (for gamma attenuation). The inner steel shell provides a minimum structural and maintenance shielding function, whereas the lead–concrete pair dominates the total dose reduction.

The shielding performance is modeled using a point-kernel transport approach, with neutrons attenuated via removal cross sections and gamma rays attenuated via linear attenuation coefficients plus a generalized buildup factor (GP). The total dose rate at the external monitoring point is expressed as:

$$D_{tot} = S[D_{0,n}\exp\left(-\sum_i \Sigma_{r,i} t_i\right) + D_{0,\gamma} B_w(X_w) B_s(X_s) \exp\left(-\sum_i \mu_i t_i\right)]$$

where $S$ is a calibration factor (determined such that the lower-bound thickness yields 100 mSv/yr at the watch-stander position), $D_{0,n}$ and $D_{0,\gamma}$ are source normalization constants, $t_i$ is the thickness of layer $i$, and $\Sigma_{r,i}$ and $\mu_i$ are the neutron removal cross section and gamma attenuation coefficient, respectively. The buildup factors $B_w$ and $B_s$ account for water-like and steel/lead/concrete-like media contributions.

**Table 3. NS Savannah radial shielding configuration**

<table>
<tr><th>Category</th><th>density (g/cm³)</th><td rowspan="7"></td></tr>
<tr><td>Core (Fuel/Water)</td><td>4.26</td></tr>
<tr><td>Primary water</td><td>0.98</td></tr>
<tr><td>Pressure vessel</td><td>7.85</td></tr>
<tr><td>Air and insulator</td><td>0.0012</td></tr>
<tr><td>Lead liner</td><td>11.34</td></tr>
<tr><td>Concrete</td><td>2.3</td></tr>
</table>

This configuration ensures that the inner lead layer dominates gamma attenuation, while the outer concrete layer absorbs moderate neutrons and residual gamma radiation. By adjusting the lead and concrete thickness, the optimization problem reduces to finding the minimum mass combination that satisfies the annual dose constraints.

*2.3. Radiation Source Term Modeling*

To balance fidelity and computational cost, an idealized surface source is prescribed at the core radial boundary $r = 75.3\ cm$. The maximum neutron flux from a 160 $MW_{th}$ PWR neutronic study is linearly scaled to 300 $MW_{th}$, giving $\phi_{fast} = 1.8\times10^{14}$ and $\phi_{thermal} = 8.6\times10^{13}$ $n\cdot cm^{-2}\cdot s^{-1}$ as conservative upper bounds at the boundary [5]. The surface flux to outward current $J \approx \phi/4$ (isotropic approximation) is converted and multiplied by the core lateral surface area $A=2\pi rh$ with $h = 200\ cm$:

$$S = J \times A = \frac{\emptyset_{\max}}{4} \times (2\pi rh)$$

$$S_{fast} \approx 4.26\times10^{18}\ n\cdot s^{-1},\quad S_{thermal} \approx 2.03\times10^{18}\ n\cdot s^{-1}$$

Fast-neutron energies are sampled from a Watt fission spectrum, while thermal neutrons are modeled at 0.0253 eV. The linear power scaling of boundary flux is a convenient upper-bound assumption; however, it is noted that actual fluxes depend on power density, leakage, and geometry and may deviate from strict linearity, which requires more detail analysis in the future [7].

## 3. Results

This study explores minimum-mass shielding configurations for a 300 MWth marine SMR while tightening the annual effective dose limit from 100 to 10 mSv·yr⁻¹. The decision variables are the thicknesses of lead (Pb) and concrete, and the objective is to minimize the total system mass subject to the dose constraint.

*3.1. Mass–Thickness Response to Dose Limits*

Improving shielding by increasing primary water would necessitate concurrent changes to the reactor pressure vessel (RPV) thickness and geometry, prompting requalification to high-temperature/pressure codes (e.g., ASME BPVC), procedure changes in welding and heat treatment, tighter NDE, and schedule risk; collectively these raise CAPEX sharply. For this reason the primary circuit (water/RPV) is treated as a fixed boundary condition, and the optimization is confined to the external biological shield using materials with the highest leverage on dose reduction—lead, which is effective for gamma attenuation due to its high atomic number, and concrete, which is effective for neutron slowing-down and absorption while also providing useful gamma attenuation and excellent constructability.

Relaxing the dose limit from 20 to 100 mSv·yr⁻¹ decreases both total shield mass and total shield thickness in a distinctly non-linear fashion. Relative to the 20 mSv·yr⁻¹ optimum (1,509.87 t, 188.69 cm), the 100 mSv·yr⁻¹ optimum is 1,310.18 t and 165.26 cm, i.e., a reduction of 199.69 t (≈15.3%) and 23.43 cm. This reduction is driven almost entirely by thinning the concrete layer (from 178.69 cm → 155.26 cm) while retaining the minimum lead thickness at 10.0 cm. In contrast, under the very stringent 10 mSv·yr⁻¹ target, simply increasing concrete becomes mass-inefficient and the optimizer pivots to increasing lead from 10.0 → 17.03 cm, indicating a transition to a gamma-dominated regime where high-Z shielding is more effective at the margin.

In the (lead, concrete) thickness plane, feasible designs trace dose iso-contours. The optimization therefore amounts to locating the minimum-mass point on a given iso-contour by exploiting the complementarity between lead (γ) and concrete (n). Figure 1 illustrates the mass–thickness tradeoff across dose targets; Table 4 lists the corresponding optima.

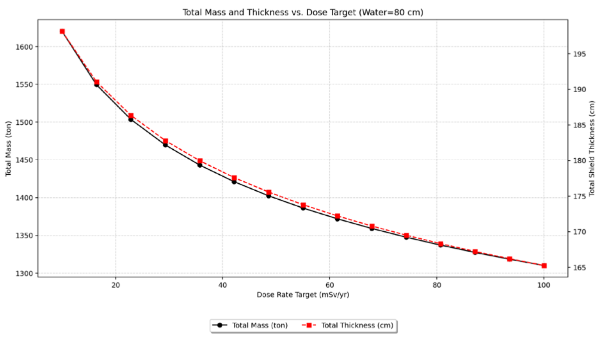



**Figure 1. Change in total shield mass and thickness as the annual dose limit is tightened.**

**Table 4. Optimal shield configurations and system mass at representative dose limits**

| Dose limit (mSv·yr⁻¹) | Lead (cm) | Concrete (cm) | Total shield (cm) | Total system mass (t) |
|---|---|---|---|---|
| 100.0 | 10.00 | 155.26 | 165.26 | 1310.18 |
| 50.0 (ICRP single-year cap) | 10.00 | 169.32 | 179.32 | 1424.89 |
| 20.0 (ICRP 5-yr average) | 10.00 | 178.69 | 188.69 | 1509.87 |
| 10.0 | 17.03 | 179.91 | 196.94 | 1614.93 |

The three-dimensional dose-rate surface (log scale on the vertical axis) over the lead–concrete plane shows an exponential-like decrease in dose as both thicknesses increase; the 100 and 20 mSv·yr⁻¹ iso-contours define the feasible fronts on which the optimizer searches for a minimum-mass point. As the target approaches 10 mSv·yr⁻¹, the surface curvature increases and the marginal effectiveness of lead becomes more pronounced, reflecting the shift toward gamma-dominated response. Figure 2 provides the corresponding visualization.

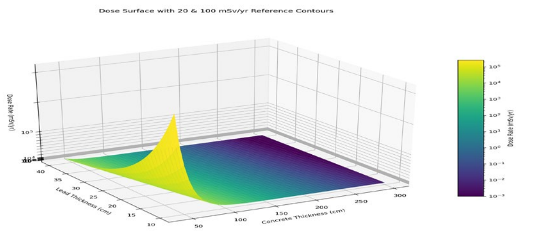



**Figure 2. Dose-rate over lead–concrete thicknesses**

The radial dose profiles for the 100 and 20 mSv·yr⁻¹ optima demonstrate the layer-wise attenuation mechanism: strong neutron moderation and absorption in the primary water plus RPV, sharp gamma suppression in the lead layer, and additional reduction of residual neutrons and gammas in the concrete. Tightening the target from 100 to 20 mSv·yr⁻¹ steepens the slope throughout the concrete region because of its increased thickness and role. Figure 3 compares these profiles.

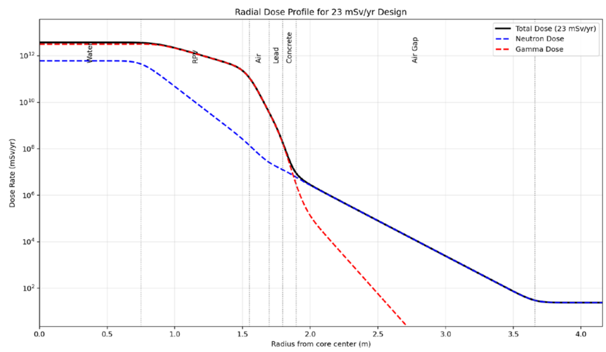



**Figure 3. Radial dose profiles for the 100 mSv·yr⁻¹**

*3.3. System- and Ship-Level Impacts with Economics*

The results of the shield design optimization have direct implications for the overall system and ship-level performance and economics. Relaxing the annual effective dose limit from 20 mSv/yr to 100 mSv/yr reduces the total shield system mass by 199.69 t (from 1,509.87 t to 1,310.18 t) and the total thickness by 23.43 cm (from 188.69 cm to 165.26 cm). This weight reduction is achieved by thinning the concrete layer while maintaining the minimum lead (Pb) thickness at 10.0 cm. Conversely, when the dose limit is tightened to 10 mSv/yr, the optimization process shifts toward increasing the thickness of the heavier lead to 17.03 cm as gamma shielding becomes more critical, resulting in a decrease in mass efficiency.

The reduced shield mass (ΔDWT) can be converted into additional cargo capacity, generating economic benefits. For a container ship, the effective extra TEUs per voyage ($n_{TEU\ eff}$) can be calculated using Equation:

$$n_{TEU\ eff} = \frac{\lambda \times \Delta DWT}{w_{TEU}}$$

Where $n_{TEU\ eff}$ is the effective extra TEUs per voyage, λ is the dimensionless mass-to-cargo conversion factor (set to 0.30), ΔDWT is the reduction in shield mass (199.69 tonnes), and $w_{TEU}$ is the average payload per TEU (10.5 tonnes).

Substituting these values into Equation (1), a mass reduction of 199.69 tonnes corresponds to approximately 5.7 additional TEUs of cargo space per voyage. This can be converted into annual additional revenue ($\Delta revenue_{year}$) using the following formula:

$$\Delta revenue_{year} = n_{TEU\ eff} \times r_{TEU} \times N$$

Where $\Delta revenue_{year}$ is the annual additional revenue (USD), $n_{TEU}$ eff is the effective extra TEUs per voyage (5.7), $r_{TEU}$ is the average revenue per TEU (assumed to be 1,200 USD), and $N$ is the number of voyages per year (assumed to be 10).

Assuming these values, the estimated annual additional revenue is approximately 68,000 USD. Considering the variability of routes and market conditions (e.g., $r_{TEU}$ = 800–1,500 USD and N = 9–11), a plausible range for annual additional revenue is 41,000 to 94,000 USD. For vessel types where deadweight is the primary constraint, such as bulk carriers or tankers (λ→1), the same ΔDWT would convert almost one-for-one into payload, implying a proportionally larger revenue effect than for container ships.

**Table 5. Summary of Key Quantitative Results**

| Parameter | 20 mSv/yr Baseline (ICRP) | 100 mSv/yr Scenario (Relaxed) |
|---|---|---|
| **Total Shield Mass** | 1,509.87 t | 1,310.18 t |
| **Mass Change vs. Baseline** | - | -199.69 t |
| **Est. Annual Revenue Gain** | - | ~ $68,000 |

## 4. Conclusions and Future Works

Traditional land-based radiation protection standards are ill-suited for Marine SMRs, which face strict mass and volume constraints driven by decarbonization goals. A marine-specific, risk-informed approach is necessary, balancing ICRP principles with the economic opportunity costs of shielding mass. This study, despite its conservative methodology, demonstrates significant design flexibility. Relaxing the annual dose limit from 20 to 100 $mSv{\cdot}yr^{-1}$ reduces optimal shield mass by approximately 199.69 t, freeing up valuable deadweight for payload. Conversely, tightening the limit to 10 $mSv{\cdot}yr^{-1}$ highlights that material selection, specifically an increased reliance on lead, becomes more critical than mere thickness. These findings advocate for a new perspective on marine nuclear shielding that integrates human protection, regulatory credibility, and ship economics.

Based on the findings of this study, several key future research directions are proposed. First, the scope of shielding optimization should be expanded to novel materials. While this study focused on lead and concrete, materials such as Boron Nitride for enhanced neutron absorption, hydrogen-rich high-density polyethylene for efficient neutron moderation, and advanced metal-polymer composites that combine structural integrity with shielding effectiveness should be investigated. The goal is to find more mass-efficient configurations that provide equivalent or superior protection with less mass and volume.

Furthermore, moving beyond the application of a single regulatory standard for all personnel, a more sophisticated, risk-informed dose limit framework should be developed. In-depth research is needed to establish a differentiated approach that considers the specific risks associated with different duties. This methodology involves setting a reasonable Lifetime Dose Limit for different personnel groups. For example, the acceptable risk for reactor-related personnel could be benchmarked against that of other radiation workers (e.g., astronauts), while the risk for general personnel could be compared to occupational hazards in other industrial environments. Adopting a career-based Lifetime Dose Limit instead of a rigid annual limit would not only enable more optimized and targeted shielding design but also allow for more flexible and efficient utilization of highly trained crew members throughout their service period.

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